TWO-DIMENSIONAL SIMULATIONS OF SAND BARRIER MOTION INDUCED BY THE EXPLOSION OF AN AMMUNITION STACK INSIDE THE MAGAZINE

William Lawrence and John Starkenberg
Ballistic Research Laboratory
Aberdeen Proving Ground, Maryland 21005-5066
Telephone: (410) 278-6210

ABSTRACT

Large quantities of explosives, frequently exceeding 100,000 lb, in different types of munitions may be stored in a single magazine. The storage of munitions has always presented safety problems, and various regulations have been developed over the years to ensure safe storage practices. In an effort to increase magazine limits, it has been proposed that the maximum credible event in an accident scenario may be significantly reduced if the munition store is divided into two or more stacks of ammunition separated by barriers designed to prevent propagation of an explosion from one stack to another. A combined analytical and experimental study was proposed to assess this hazard and to determine whether such barriers can be designed. The simulations were used to determine the velocity of a sand barrier on impact with an acceptor ammunition stack in order to design meaningful experiments. The donor ammunition stack was simulated by a volume of bare explosive. The initial position and size of the donor charge were varied in different computations. The thickness of the barrier was also varied. Velocity, pressure, and impulse histories were monitored at several stations in and near the barrier. Computational results show that the kinetic energy imparted to a barrier decreases with its thickness, indicating that thin fast-moving barriers have a potential to do greater damage to ammunition in an acceptor stack than thick slow-moving barriers. Thus, the barriers must be designed thick enough to prevent fragment penetration.

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1. INTRODUCTION

Large quantities of explosives, frequently exceeding 100,000 lb, in different types of munitions may be stored in a single magazine. The storage of ammunition has always presented safety problems, and various regulations have been developed over the years to ensure safe storage practices (DOD 6055.9 STD 1984; AR 385-64 1987). The situation is further complicated in areas where increased population density and reassessment of hazards have reduced the applicable explosive limits for existing magazines (Lyman 1983). To reduce the total land requirements for magazine facilities, it is desirable to limit the size of the maximum credible event to about 50,000 lb (further reductions don't reduce the safe inhabited building distance).

It has been suggested that the maximum credible event in an accident scenario may be significantly reduced if the munitions store is divided into two or more stacks of ammunition separated by barriers designed to prevent propagation of an explosion from one stack to another caused by fragments from the donor stack. For typical stacks of ammunition, this may require a wall of sandbags about 1 m thick. When using such a barrier to intercept fragments, the problem of the effect of its impact on the acceptor stack arises. While the fragment hazard may be eliminated, the moving barrier may cause sufficient damage to the munitions in the acceptor stack to initiate the explosive they contain, thus defeating its intended purpose.

A combined analytical and experimental investigation was proposed to assess this hazard and to determine whether such barriers can successfully be designed. The analytical study, which has been completed, included three numerical simulations using the HULL code. The first simulation was used to determine the velocity of the barrier on impact with the acceptor stack in the magazine environment in order to design meaningful experiments. In addition, several barrier design issues were addressed analytically. The second simulation was used to determine the experimental configuration required to produce the desired barrier velocity. The final simulation was used to assess the loading on typical acceptor ammunition that might be anticipated, in order to determine instrumentation requirements.

2. DESCRIPTION OF THE MAGAZINE AND AMMUNITION STACKS

Munitions must be stored such that they can be easily accessed, inspected, and inventoried. Dissimilar items are stored together, and each type must be available for removal without disturbing other stored munitions. Much of the munitions stockpile is stored in standard magazines. Elevation and plan views of such a structure including a proposed stack arrangement are shown in Figure 1.

The magazine is constructed with reinforced concrete walls, roof, and floor and is covered with earth. The interior of the magazine is semicylindrical, 24.38 m long and 8.00 m in diameter. A steel door, 1.22 m (4 ft) wide by 2.44 m (8 ft) high, is located in the middle of one of the end walls. The door is used for access in order to store or remove ammunition and also serves as a vent in case of an explosion inside the magazine.

Using palletized M107 155-mm projectiles, it is possible to store 506 pallets in a stack 3.35 m deep, reaching to the roof of the magazine. The high explosive weight per pallet is approximately 55.9 kg (123 lb), which gives 28,290 kg (62,238 lb) per stack. Up to four such stacks could be stored in a magazine, while still leaving room for barriers up to 1 m thick and 1 m of access space on each side of each stack.

3. DESCRIPTION OF THE PROPOSED EXPERIMENT

It is clearly impractical to conduct full-scale tests of candidate magazine configurations in order to find an arrangement which produces the desired results. As an alternative, tests in which a barrier segment is launched at a representative velocity toward an acceptor stack

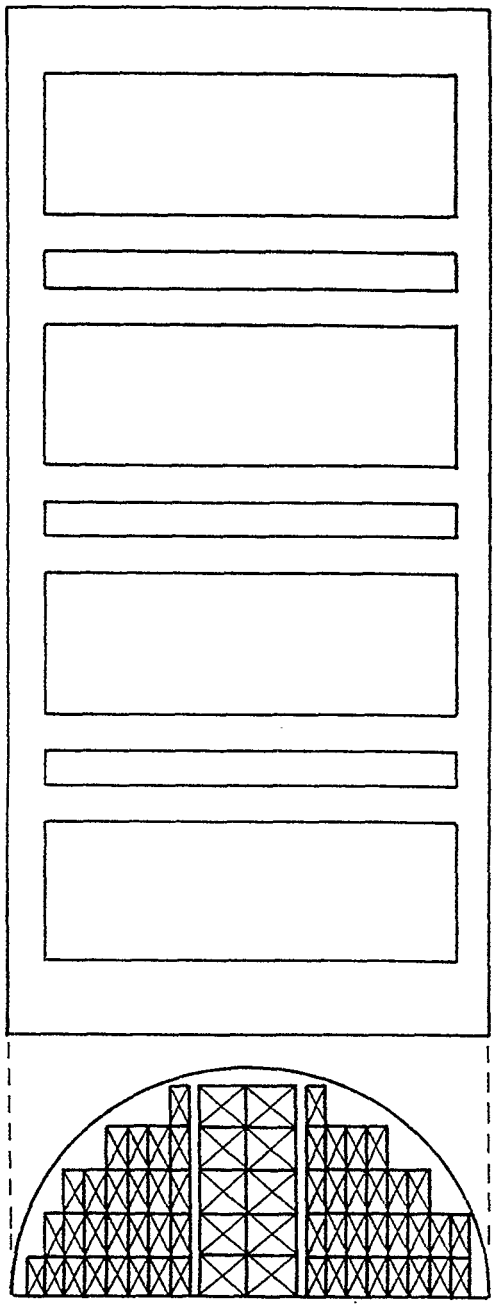


Figure 1. End Elevation and Plan Views of a Typical Magazine Showing a Proposed Stacking Arrangement.

segment have been proposed. In these tests, the barrier thickness remains full-scale, but its lateral extent is limited.

The test setup is illustrated schematically in Figure 2. In order to account for the lateral confinement provided by the full magazine environment, the tests are conducted in a trench 2 m deep, 3 m wide, and about 10 m long with a 2-m-thick earth overburden. The configuration is symmetrical, allowing two barriers to be launched toward two acceptor stacks by a central ammonium nitrate - fuel oil (ANFO) charge. The acceptor stacks include both live and inert 155-mm ammunition.

4. BRIEF DESCRIPTION OF THE HULL CODE

We used the HULL code to conduct the analytical study. The HULL system consists of programs for generating and solving two- and three-dimensional dynamic continuum mechanics problems in Eulerian and/or Lagrangian frameworks plus many peripheral programs required to provide graphical renditions of the results. Numerous constitutive models are included, and material parameters are provided in the HULL library. Detonation is treated by the programmed burn method. We used the two-dimensional Eulerian finite-difference capability (without heat conduction or viscosity) for our simulation and the graphics routines to obtain pressure and density contour plots as well as history plots (Hull User's Class).

5. DESCRIPTION OF THE MAGAZINE SIMULATION

In order to keep the size of the simulation manageable, we used a two-dimensional axisymmetric representation of the magazine as illustrated in Figure 3. The simulated magazine is thus a complete cylindrical shell structure having twice the interior volume of the actual semicylindrical magazine. Because of the absence of any angular motion component, a plane of symmetry exists at the magazine floor (or any similar plane), effectively providing a perfectly rigid surface.

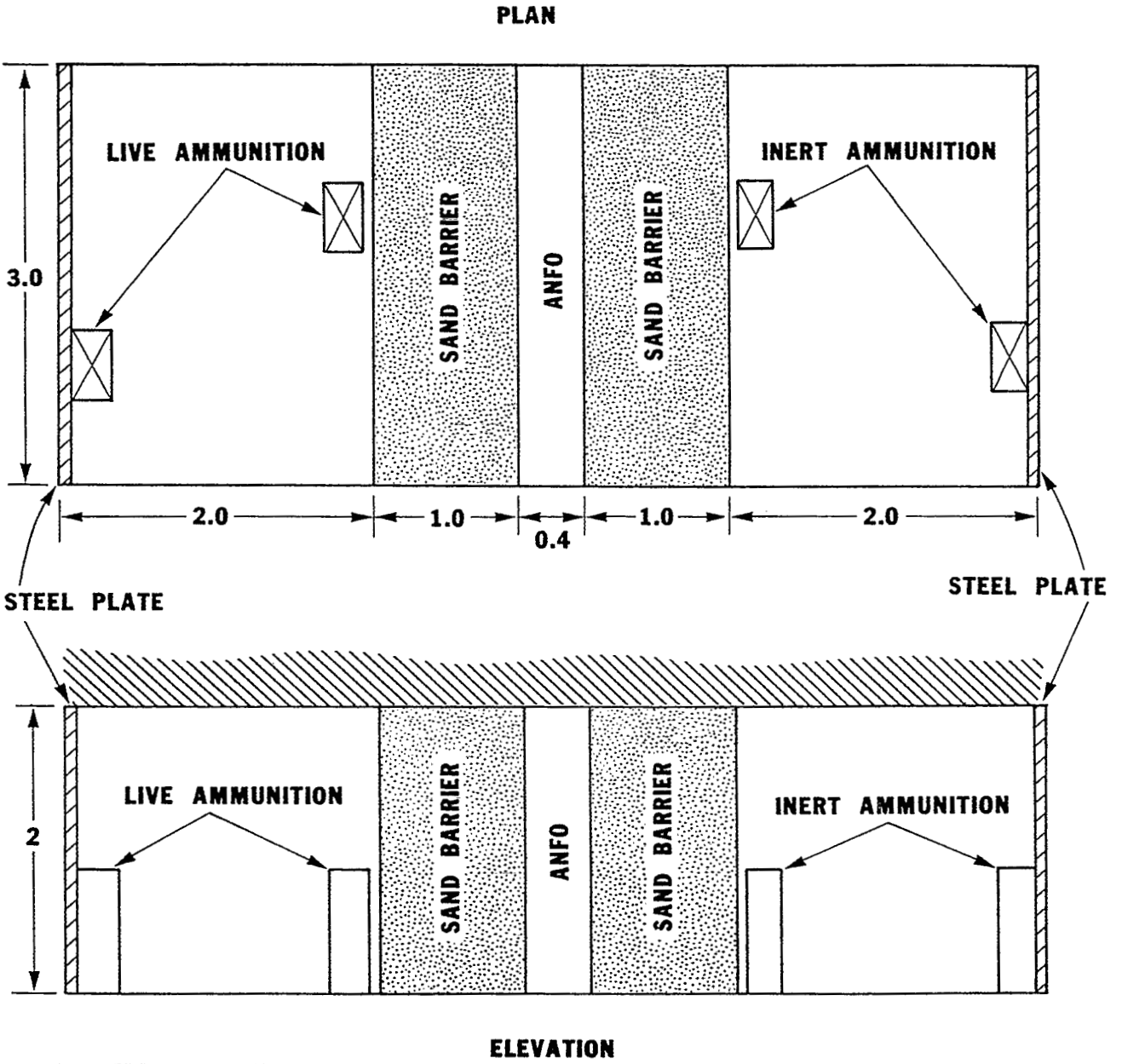


Figure 2. Side Elevation and Plan Views of the Proposed Experimental Arrangement.

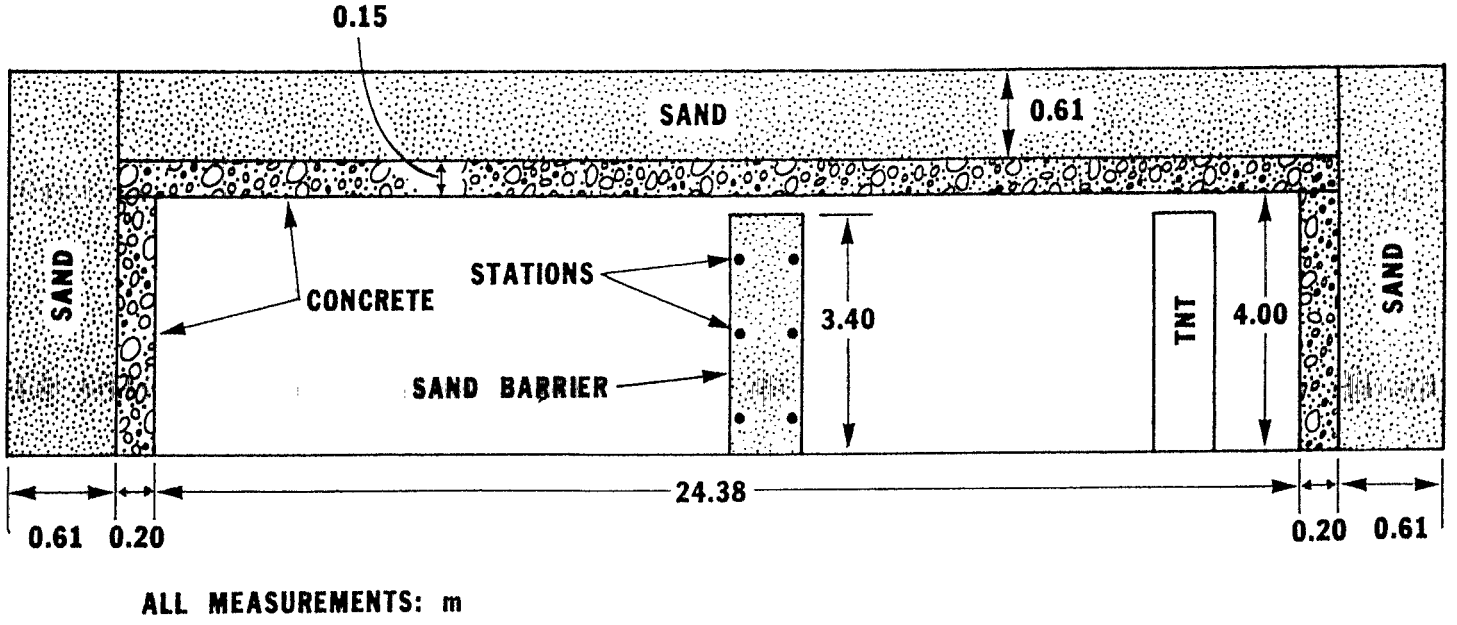


Figure 3. Magazine Configuration Simulation.

A concrete shell and end walls enclose the air-filled interior of the magazine, and a sand layer simulates the earth overburden. Air also fills the region surrounding the magazine. No attempt was made to represent the doors.

The donor ammunition stack is simulated by a cylinder of bare TNT representing (in the baseline case) 56.5 Mg (about 124,000 lb) or twice the actual mass (corresponding to the doubling of the interior volume). The initial position of the donor charge and its mass was varied in different computations. In each case, it was initiated on the axis at the center of the charge.

A sand barrier is placed near the center of the magazine. Sand wall thicknesses varying from 1 m to 3 m were modeled in different computations. In a few computations, vents (or open spaces) were left in the barriers to facilitate pressure equilibration across them. The vents were placed 1.0, 2.2, and 3.4 m above the floor. The size of the vents ranged from 0.20 to 0.60 m. Several stations in and near the sand barrier were chosen for monitoring velocity, pressure, and impulse histories. These are shown in Figure 4.

The computational region was discretized into 350 zones covering 28 m in the axial direction and 75 zones covering 6 m in the radial direction.

Equations of state for air, concrete, sand, and TNT products (Jones-Wilkins-Lee [JWL]) were taken from the materials library of the HULL code.

6. RESULTS OF THE MAGAZINE SIMULATION

Figures 5a through 5e shows a series of pressure and density contour plots for a typical computation. Pressure contours are shown on the left side of the axis and density on the right. After the TNT detonated, it took about 3 to 4 ms for the blast wave to arrive at the sand barrier. Acceleration of the wall took place over a considerably longer period of time. Each computation was allowed to run for 30 to 40 ms. This was more than enough time to produce a steady wall velocity. The contour plots show increasing diffusion of the material boundaries

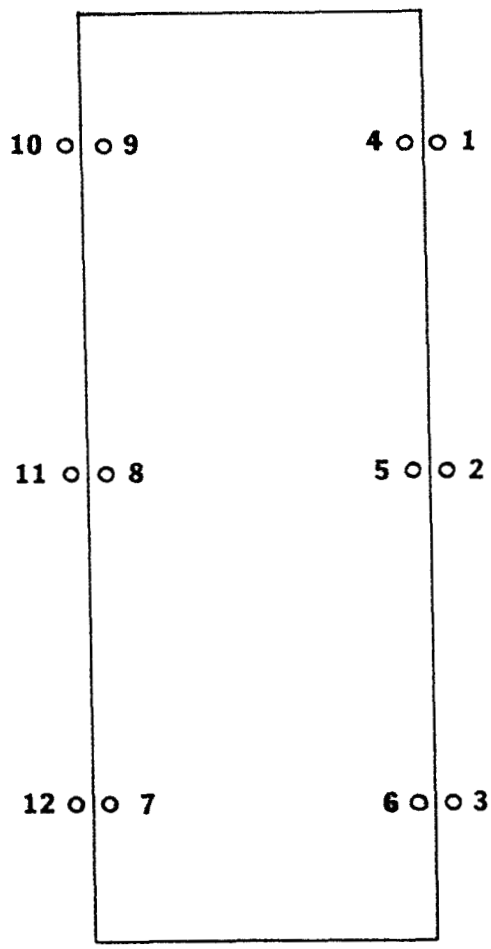


Figure 4. Locations of the Lagrangian Stations In and Near the Barrier.

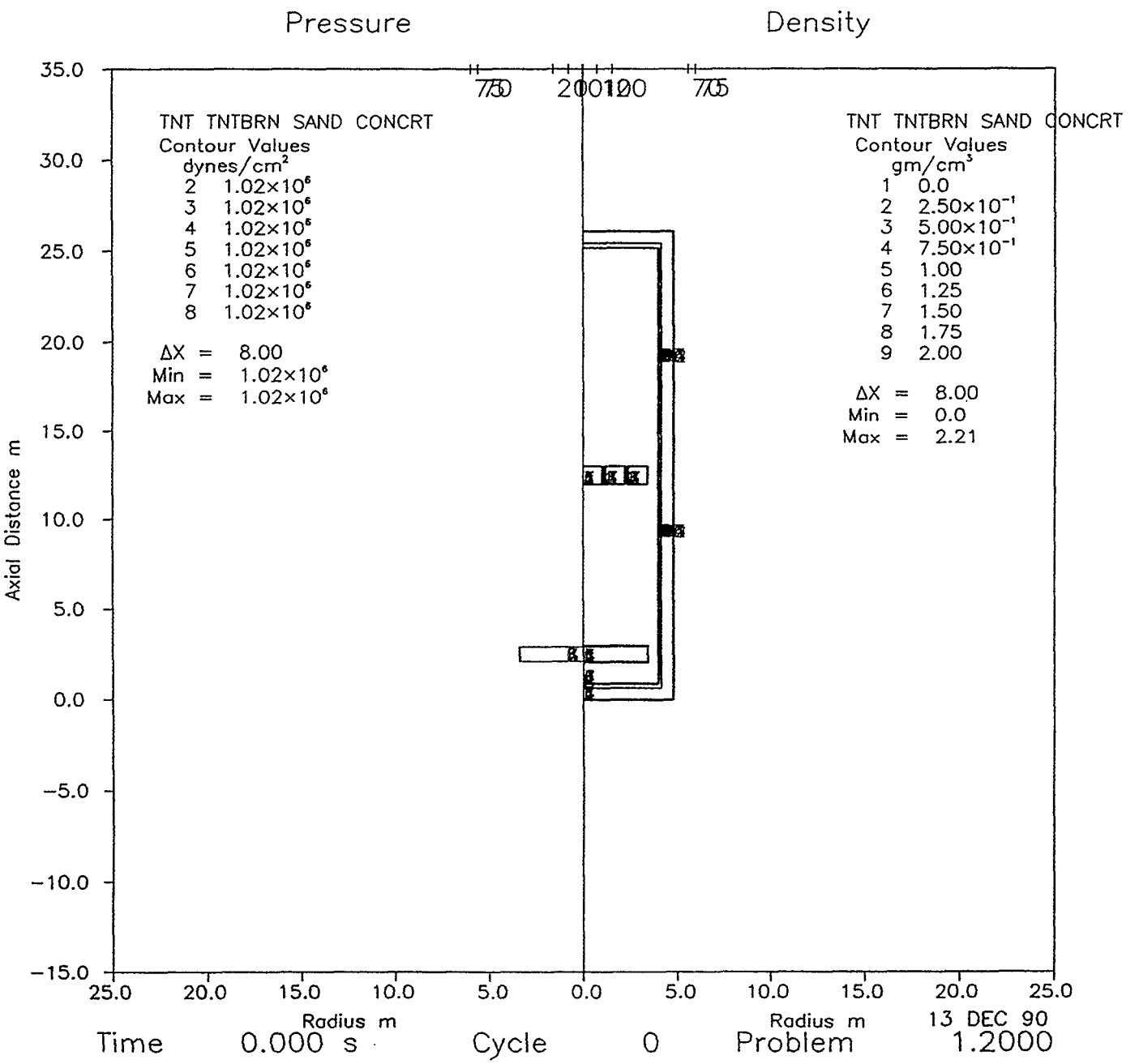


Figure 5a. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 0 ms.

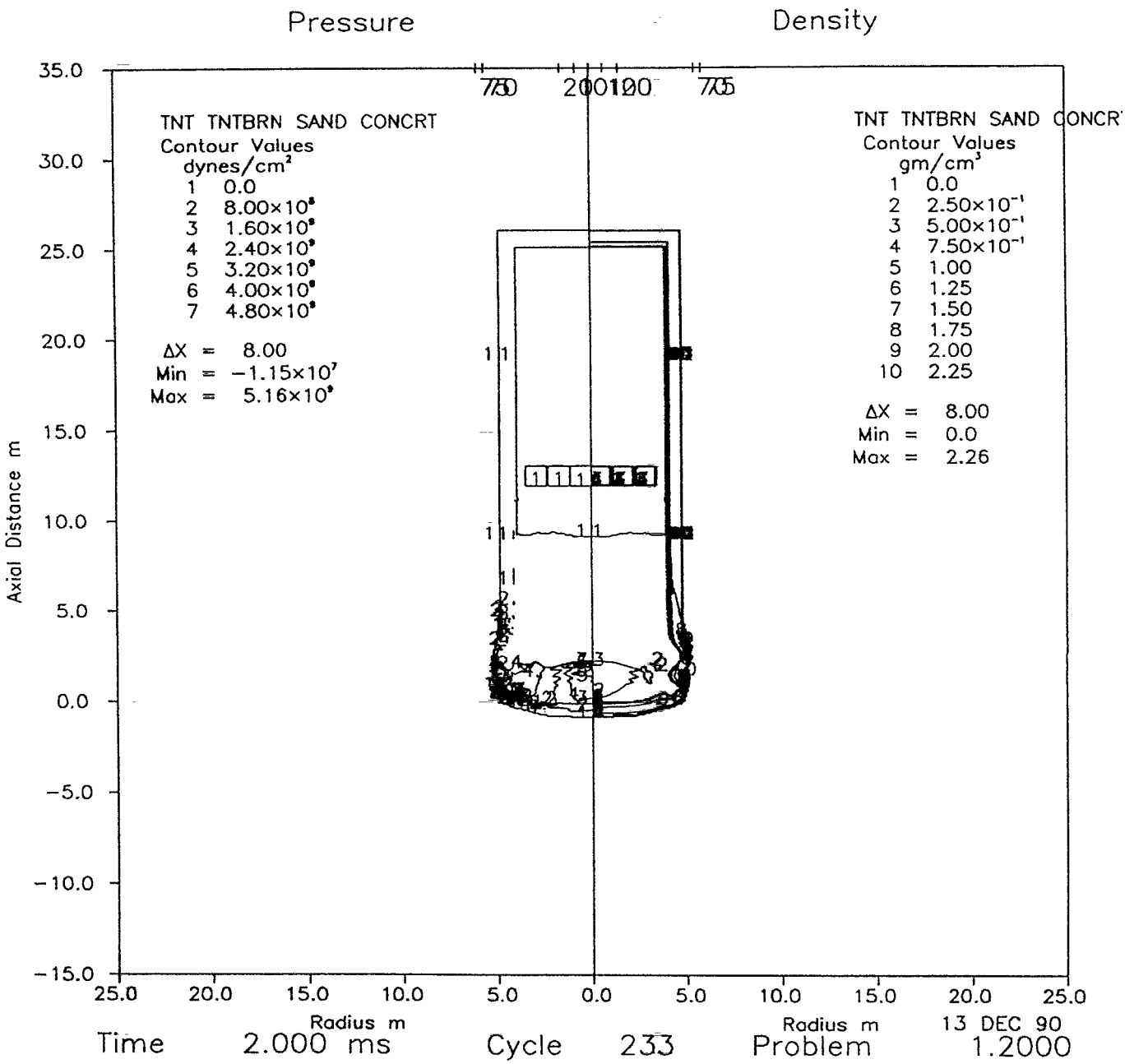


Figure 5b. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 2 ms.

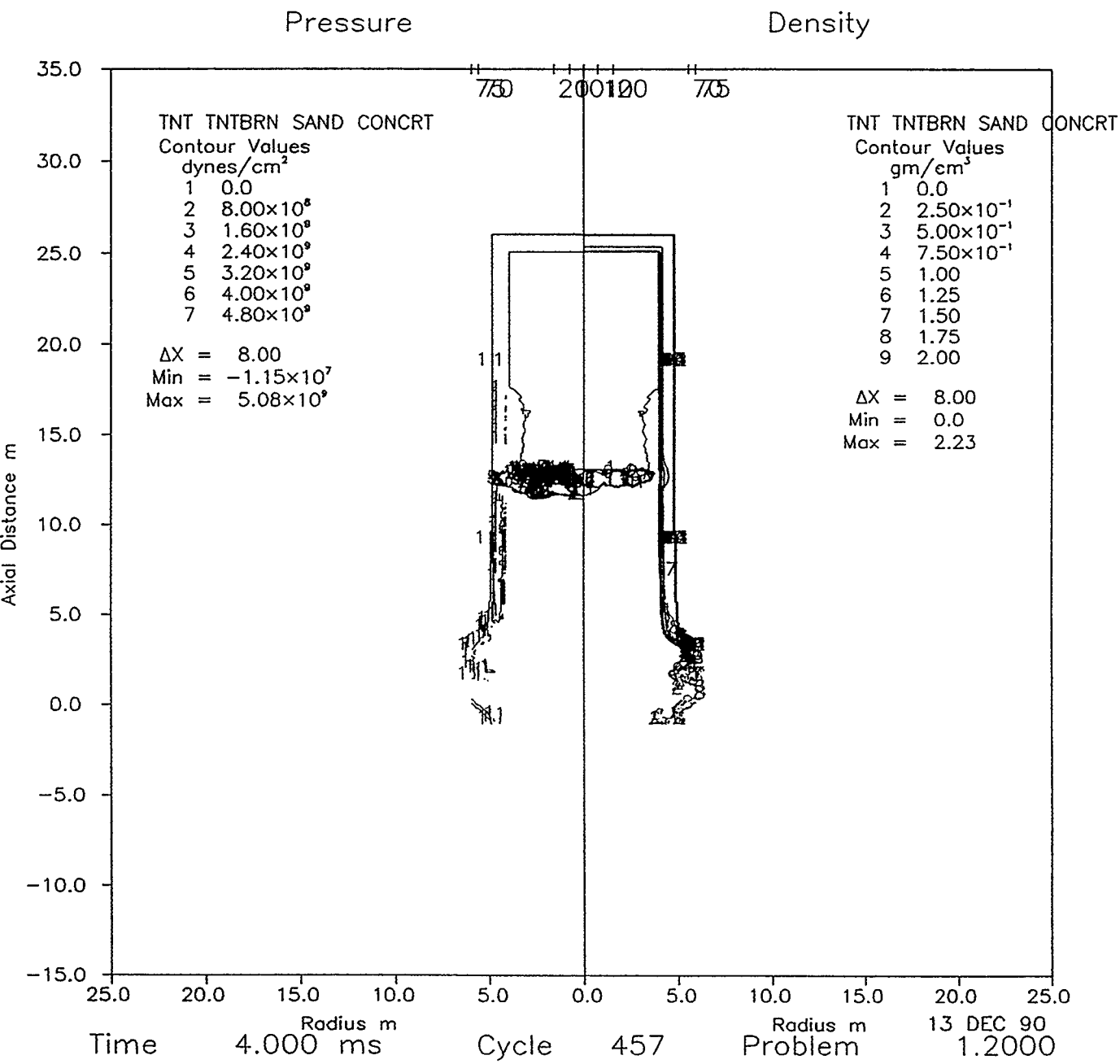


Figure 5c. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 4 ms.

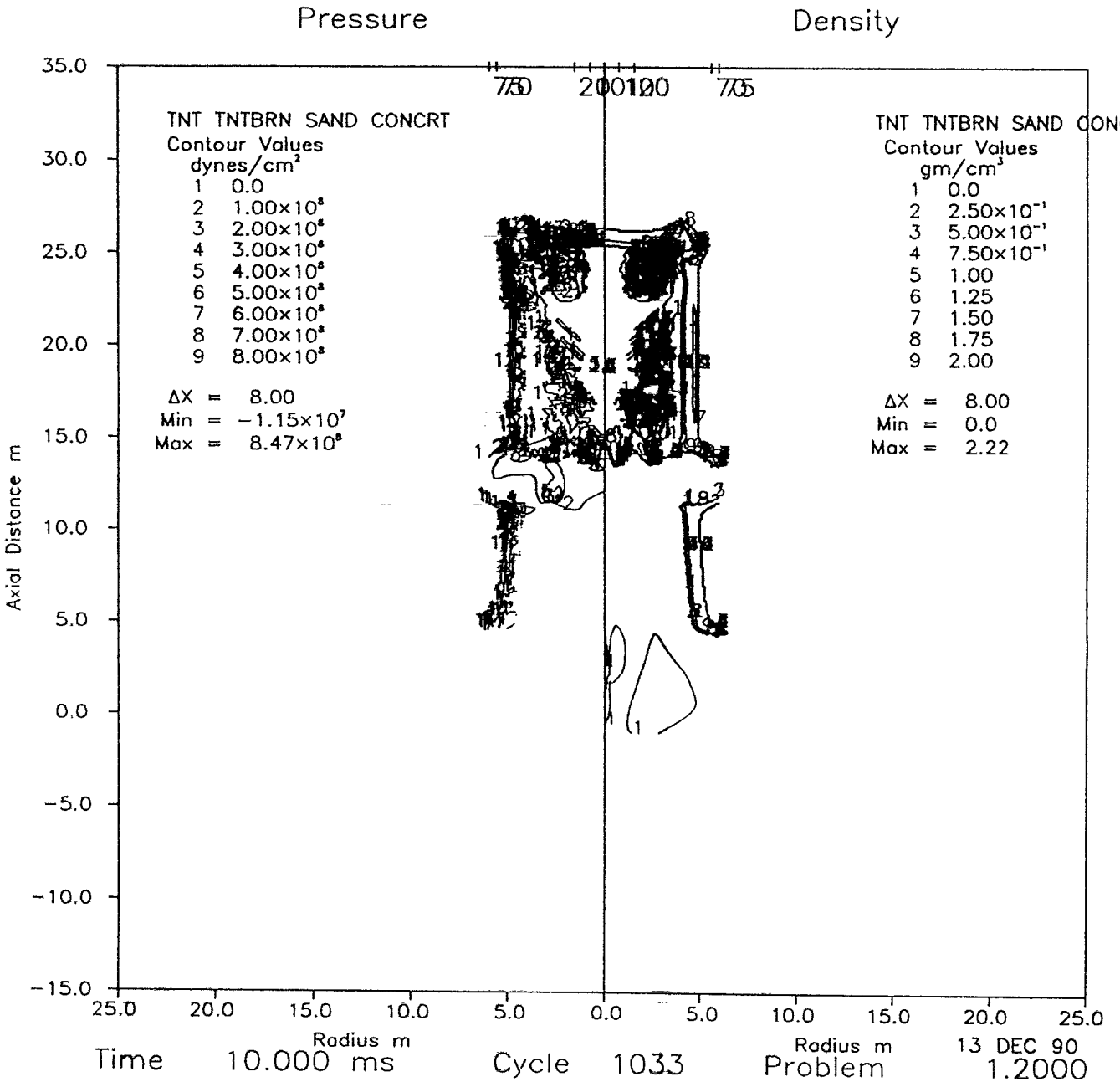


Figure 5d. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 10.0 ms.

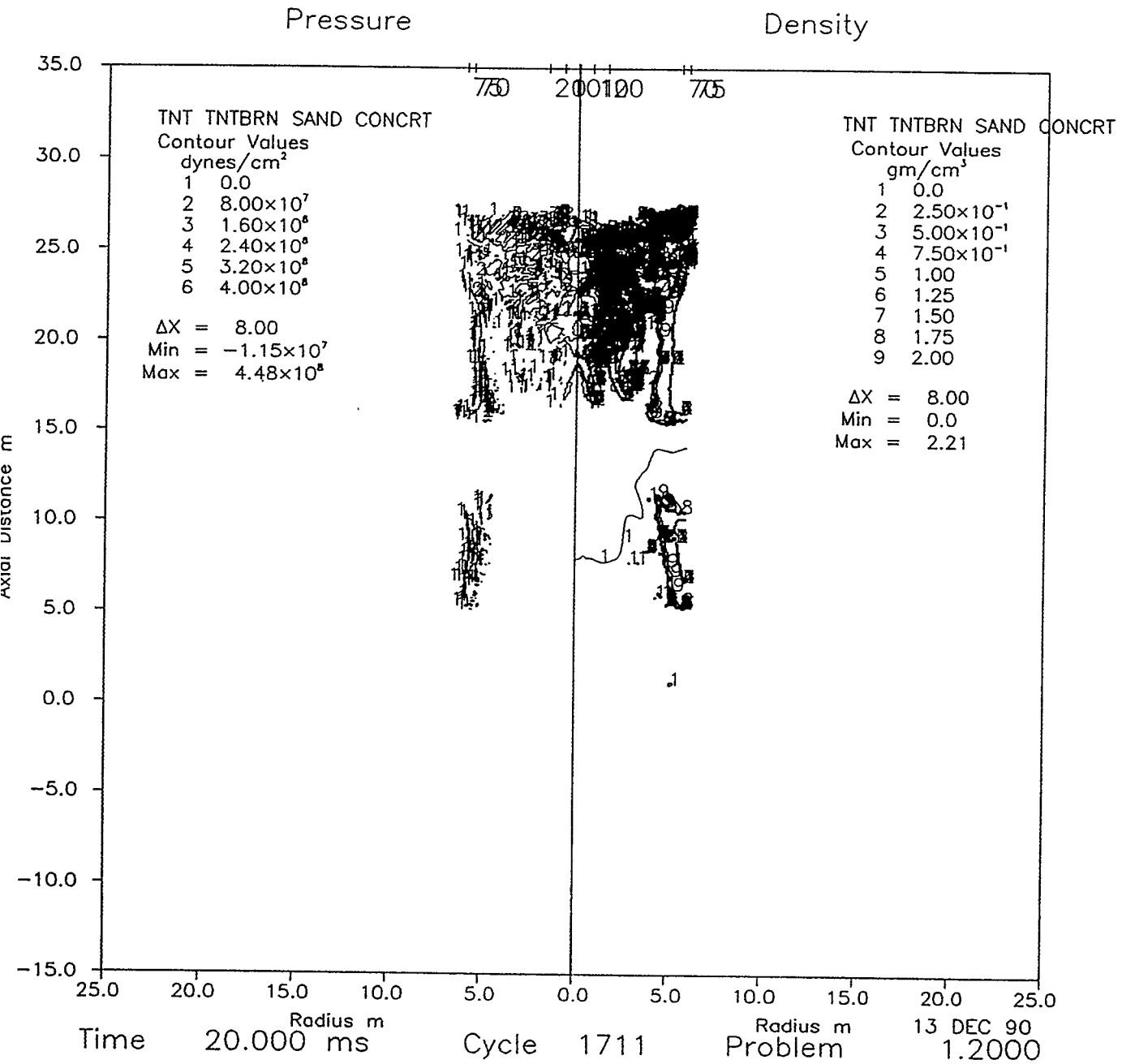


Figure 5e. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 20.0 ms.

at late time. Corresponding plots of velocity history at several of the stations are shown in Figure 6. Somewhat different steady-state values are produced at the different stations. A total of 18 computations were completed. The steady-state velocities computed at stations 7, 8, and 9 (near the leading edge of the barrier) are summarized in Table 1 along with the average velocity at all the stations in the barrier. Some variation in the velocity from station to station is evident, but the general trends remain clear.

As the barrier thickness is increased while retaining a separation of 5.0 m between the center of the charge and the center of the barrier with a 28.2-Mg charge, the resulting terminal velocity decreases. Average terminal velocity is plotted as a function of barrier thickness in Figure 7a. As the separation distance is increased, the terminal velocity decreases as shown in Figure 7b. Approximate representations of the barrier momentum and kinetic energy per unit area may be obtained by multiplying the initial barrier mass per unit area by the velocity and half the square of the velocity, respectively. These are plotted as functions of barrier thickness in Figure 8. The results are most consistent with constant momentum and show decreasing kinetic energy with increasing thickness.

Venting of the barriers left their terminal velocities virtually unchanged as is evident in Table 1.

The distances between the barrier and the donor charge and the mass of the donor charge were also varied in different computations. Blast scaling laws suggest that the impulse delivered, and, hence, the terminal momentum of the barrier, is a function of the scale distance defined by dividing the physical distance by the cube root of the charge mass. The variations in approximate terminal momentum as a function of scale distance are shown in Figure 9. The results indicate that this relationship is reasonably well followed especially at larger scale distances.

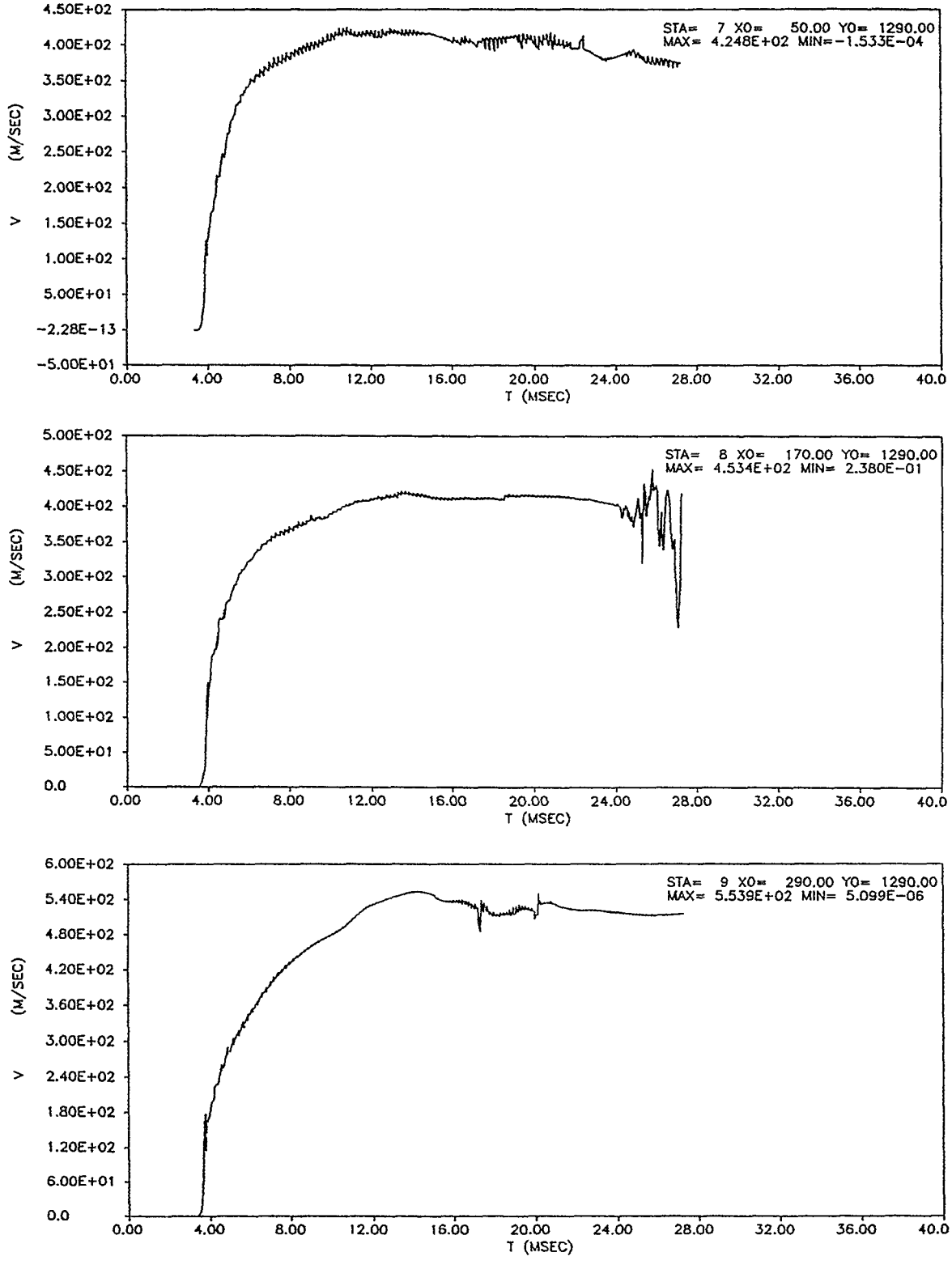


Figure 6. Velocity Histories at Several Lagrangian Stations for a Representative Magazine Simulation Computation.

Table 1. Summary of Magazine Computations

Charge Mass (Mg)	Barrier Thickness (m)	Center-to-Center Separation (m)	Terminal Velocity at Station 7 (m/s)	8 (m/s)	9 (m/s)	Average Terminal Velocity (m/s)
19.5	2.0	5.0	200	200	170	208
28.2	0.5	5.0	900	900	800	867
28.2	1.0	5.0	500	560	460	514
28.2	1.0	10.0	440	385	510	437
28.2	1.0[a]	10.0	420	400	500	443
28.2	1.0	11.0	450	400	530	415
28.2	2.0	5.0	320	290	255	290
28.2	2.0	5.5	300	280	235	282
28.2	2.0	7.5	225	230	190	224
28.2	2.0	10.5	240	240	230	210
28.2	2.0[a]	10.5	220	240	210	206
28.2	3.0	5.0	200	200	160	195
28.2	3.0	6.0	180	180	140	172
28.2	3.0	8.0	150	150	100	158
28.2	3.0	11.0	120	140	115	142
28.2	3.0[a]	11.0	120	120	140	128
32.4	2.0	5.0	360	360	320	328
37.0	2.0	5.0	400	400	400	380

[a]vented barrier

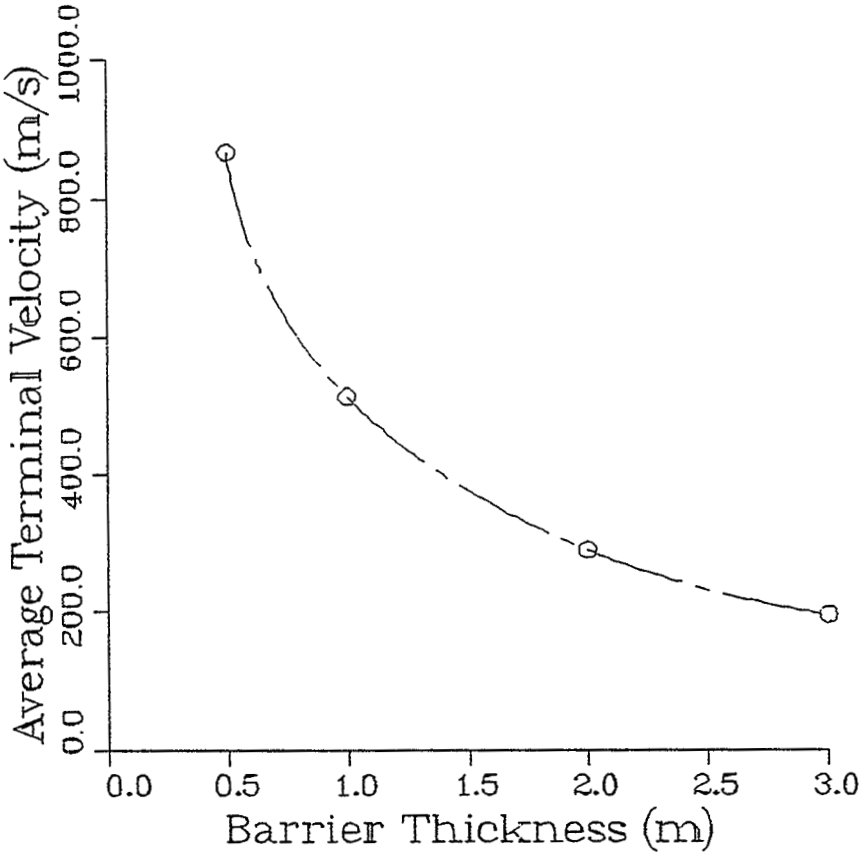


Figure 7a. Average Terminal Velocity as a Function of Barrier Thickness for a Charge Center to Barrier Center Separation Distance of 5.0 m.

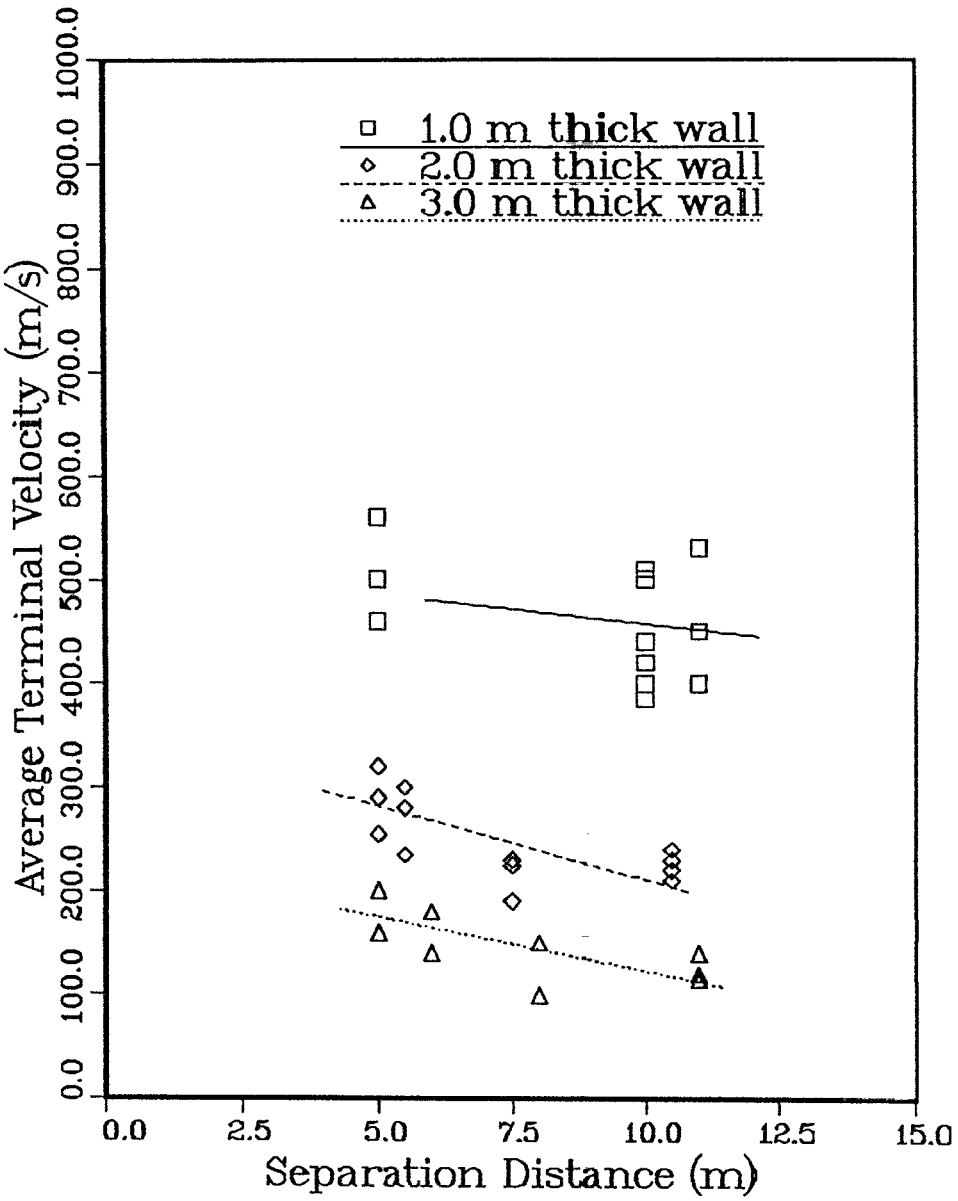
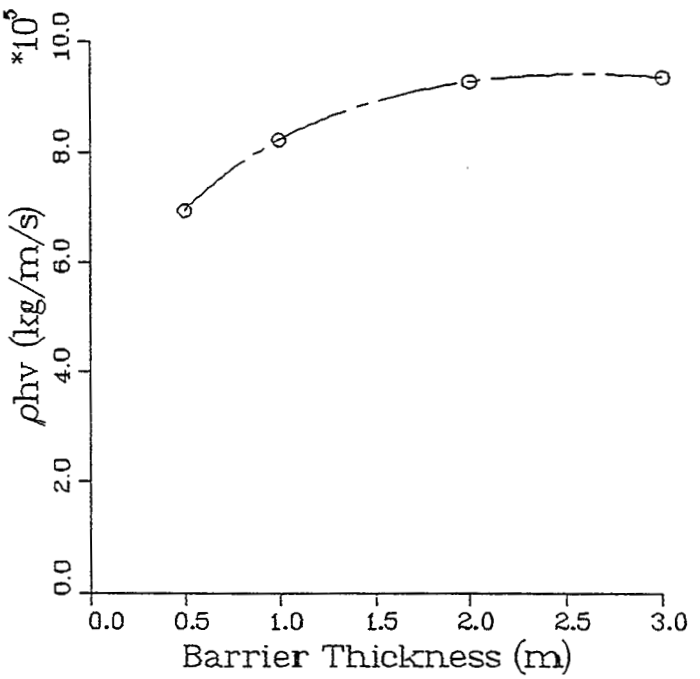


Figure 7b. Average Terminal Velocity as a Function of Separation Distance.



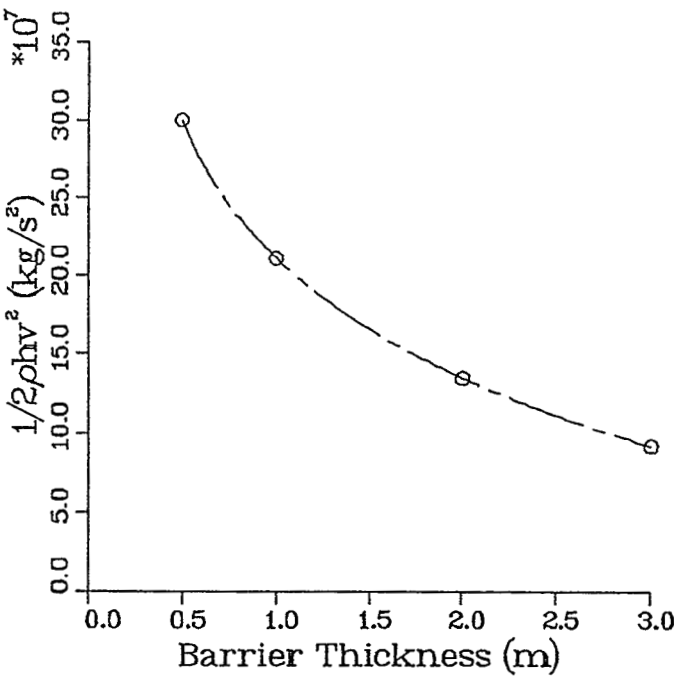


Figure 8. Approximate Terminal Momentum and Kinetic Energy as Functions of Barrier Thickness for a Charge Center to Barrier Center Separation Distance of 5.0 m.

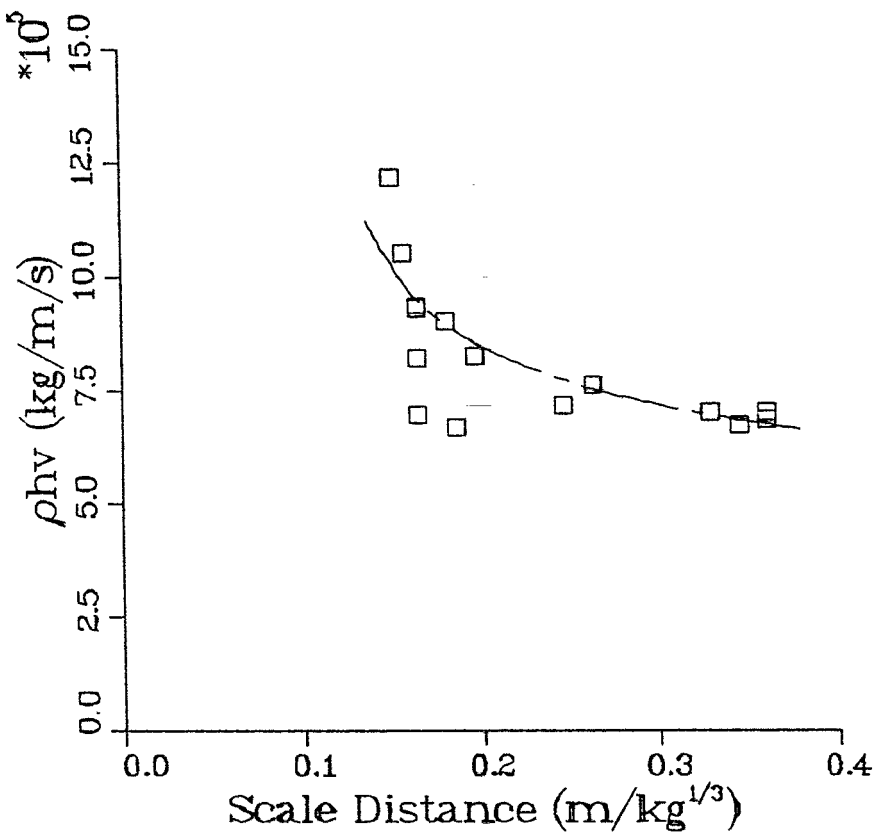


Figure 9. Approximate Terminal Momentum as a Function of Scale for All Computation.

7. DESCRIPTION AND RESULTS OF THE TEST SIMULATION

A simulation of the experimental configuration, as illustrated in Figure 10, was also made. Axisymmetry was deemed the best way to represent the lateral confinement in a two-dimensional simulation. Additional symmetry is afforded by the experimental setup in which identical sand-filled barriers are arranged on either side of a TNT or ANFO charge which fills the space between them. The computational region thus extends from the center of the charge (where a reflective plane is placed) to a point 2 m beyond the end of the trench. The thickness of the barrier was maintained at 1 m in all the computations, but the thickness of the charge was varied from 0.30 to 0.40 m in different computations. The velocity of the wall was monitored at three locations (r=0.50, 1.00, and 1.50 m) along the radial axis, as shown in Figure 10.

Representative velocity histories are shown in Figure 11. Because the driving explosive is initially in contact with the barrier, the barrier does not quite reach terminal velocity before striking the end of the trench. The maximum velocities determined in four computations are summarized in Table 2.

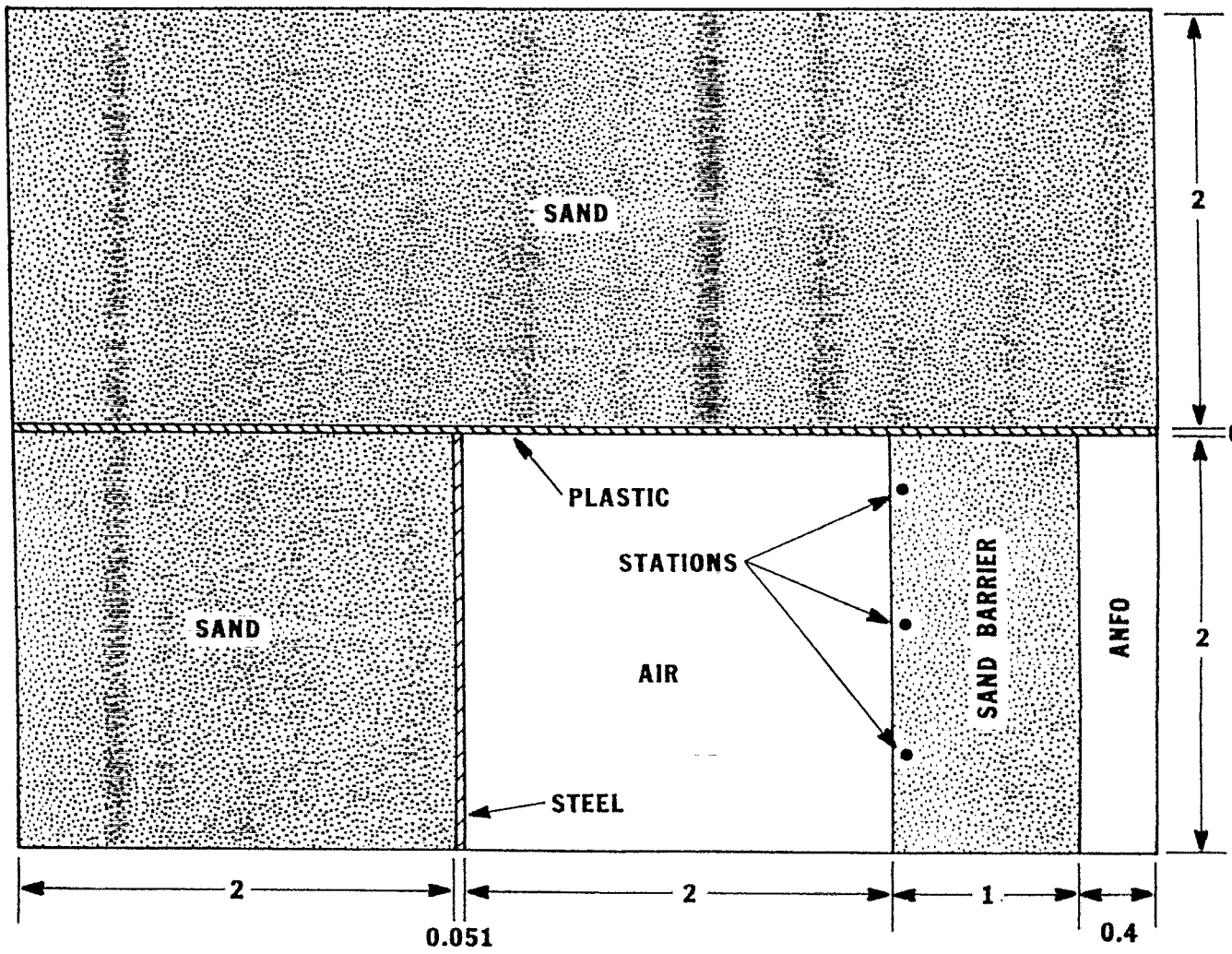


Figure 10. Experiment Simulation Configuration Showing the Locations of the Lagrangian Stations.

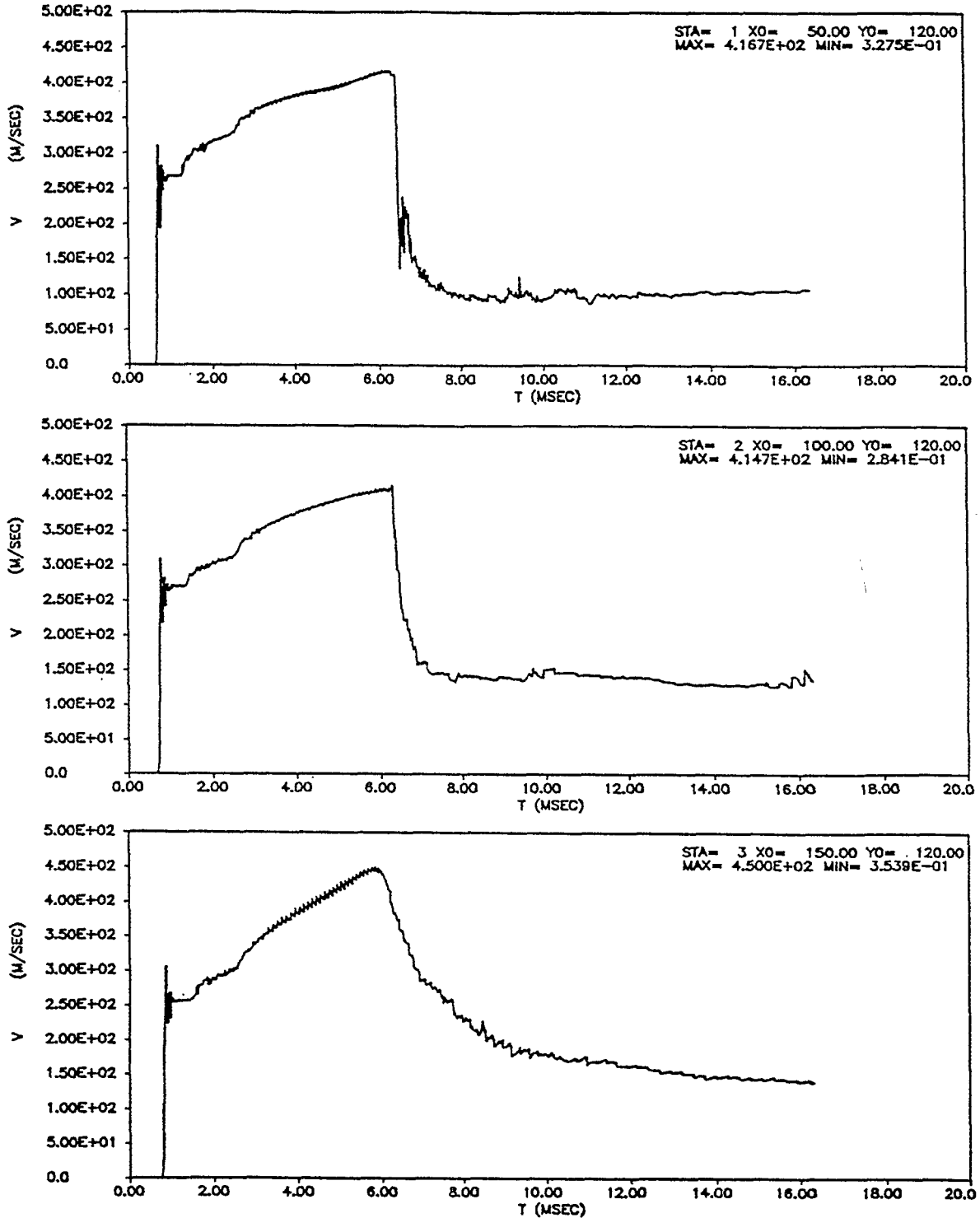


Figure 11. Velocity Histories at Several Lagrangian Stations for a Representative Test Simulation Computation.

Table 2. Summary of Test Simulation Computations

Charge Explosive	Thickness (m)	Maximum Velocity at Station 1 (m/s)	2 (m/s)	3 (m/s)	Average Velocity (m/s)
TNT	0.20	270	280	320	290
TNT	0.30	450	450	480	460
ANFO	0.30	320	320	350	330
ANFO	0.40	400	400	450	417

8. DESCRIPTION AND RESULTS OF THE ACCEPTOR RESPONSE SIMULATION

A final calculation was made to determine the pressure that might be expected inside a 155-mm M107 artillery round subjected to barrier impact at 360 m/s. The problem configuration including the locations of the pressure monitoring stations is shown in Figure 12. The computed pressure histories are shown in Figure 13. The pressures observed were generally lower than 0.35 GPa.

9. SUMMARY AND CONCLUSIONS

The fact that the kinetic energy imparted to a barrier decreases with its thickness indicates that thin fast-moving barriers have the potential to do greater damage to ammunition in an acceptor stack than thick slow-moving barriers. Barriers must be designed thick enough to prevent fragment penetration. Additional thickness, where possible, is also desirable.

The terminal momentum of the barriers was found to be roughly constant for a given charge mass and location. The application of blast scaling laws showed that these might be useful as predictive tools when the distance between stack and barrier is not too small.

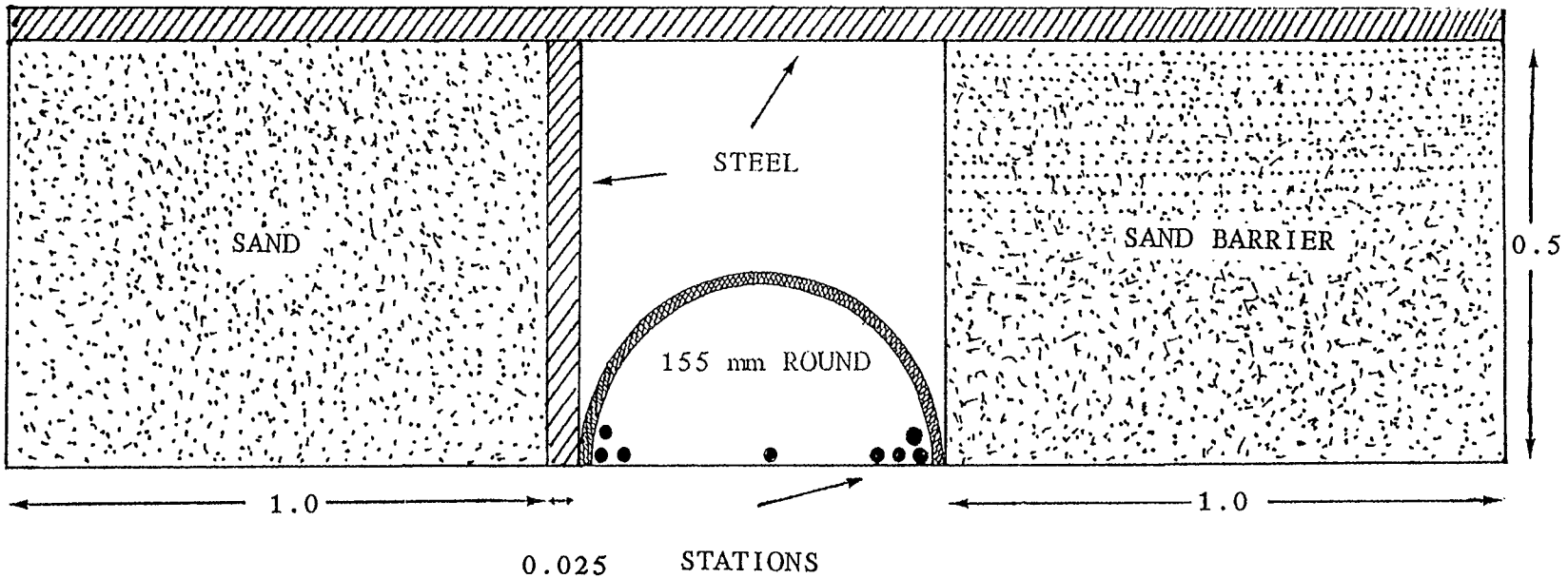


Figure 12. Munition Response Simulation Configuration Showing the Locations of the Lagrangian Stations.

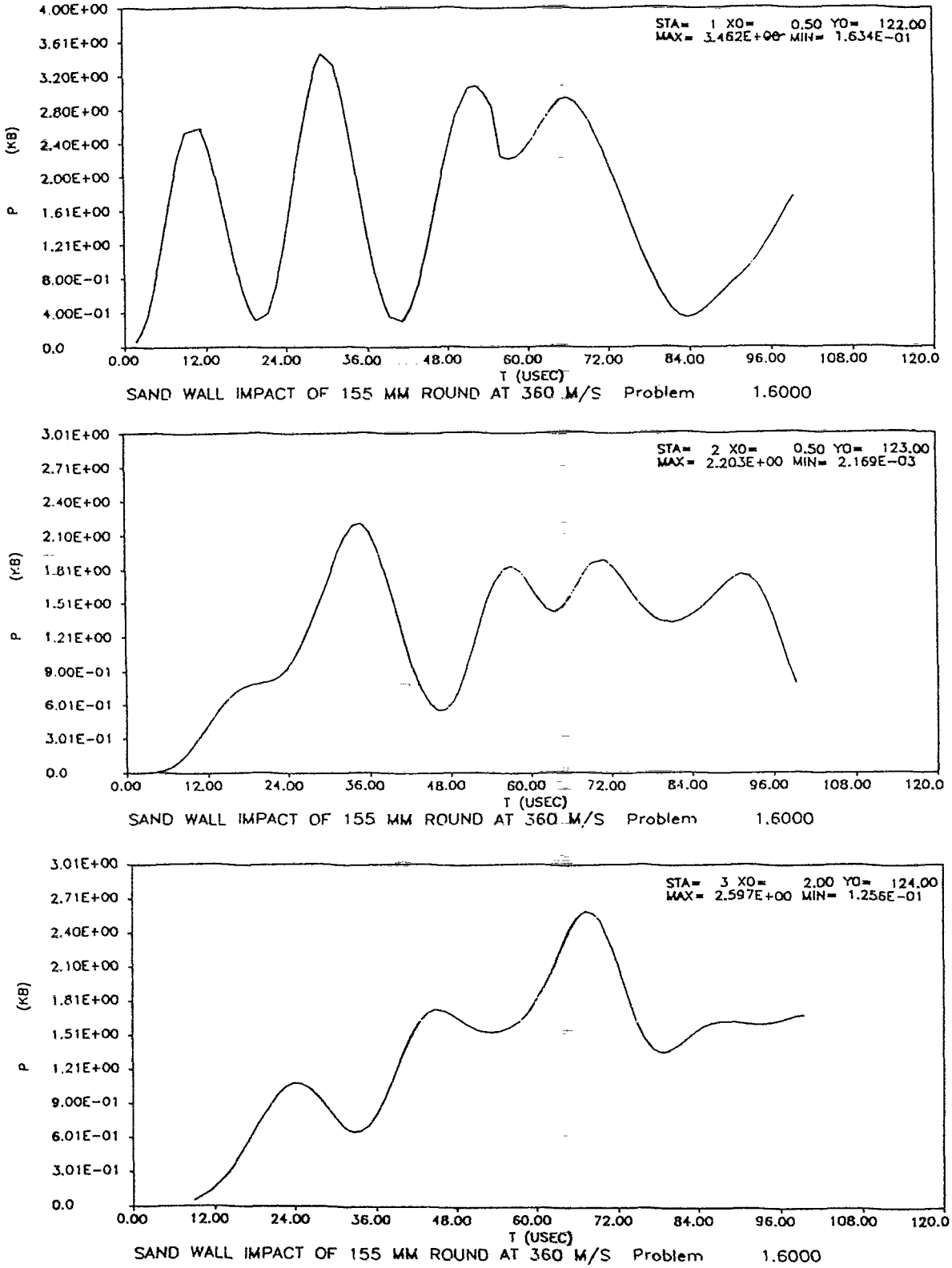


Figure 13. Pressure Histories at the Lagrangian Stations for the Munition Response Simulation.

Terminal velocities were not significantly reduced when vents were placed in the barriers. Thus, these computations provide little support for this technique as a method for mitigating the hazard posed by moving barriers.

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